Development of a New Approach to Core Quality Assessment of Modern Electrical Machines

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***Abstract*- Hysteresis behavior of the magnetic materials is an interesting physical concept and has important practical applications in physics and engineering. In this paper a new approach is developed to evaluate the quality of magnetic cores, based on the measured dynamic hysteresis loop. In this study, artificial inter-laminar faults of different configurations were applied on stacks of four standard Epstein size laminations of 3 % grain oriented silicon steel. Dynamic hysteresis loop of the samples were measured and analysed over a range of magnetising frequency and flux density, to calculate the extra power losses caused by the artificial faults. The results shows an accurate evaluation of the extra power loss compare to the bulk measurement, with a maximum difference of less than 4 %.**

Index Terms: Inter-laminar fault, soft magnetic material, grain-oriented steel, dynamic hysteresis loop, magnetic loss, core quality.

1. Introduction

Electrical steels are key materials of electrical machines and transformers. Standardised experimental methods are available to characterise performance of the electrical steels over a range of magnetisation [1-2]. Mechanical, magnetic and electric properties of electrical steels can be deteriorated by manufacturing process, e.g. cutting, pressing and welding, which has a direct impact on normal operation of the magnetic cores [3-4]. Quality of the magnetic cores is an important factor for the designers, manufacturers and users of the magnetic devices. Core quality mainly depends on electrical and magnetic properties of the magnetic material, quality of the insulation material, which determines the inter-laminar resistance between the adjacent laminations, clamping pressure, magnetising condition, etc. Key amongst these are inter-laminar faults which have been identified as a major threat for normal operation of electrical machines and transformers [3-9].

Inter-laminar fault leads to circulating eddy current between the defective laminations, which is known as inter-laminar fault current. Typically, fault current loops are formed between the shorted laminations and fault points which are perpendicular to the direction of the magnetic flux in the core [4-5]. Inter-laminar fault, which leads to inter-laminar fault current, is one of the most serious concerns for the manufacturers and customers of the electrical steels [1-9]. A few faults may not create high inter-laminar fault currents; but with several faults in the core, the induced inter-laminar fault currents could be large and cause excessive local heating in the damaged area [8-10]. Whereas a large number of inter-laminar faults can lead to catastrophic failure, the machine can still operate with a limited number of inter-laminar faults, but with elevated power loss. Local power loss results in hot spots in the core, which accelerate the degradation of the insulation coating of the laminations and can causes premature aging of the magnetic cores. Inter-laminar faults analysis and detection in the stator core of the rotating machines could be more complicated compare to the transformer cores [4]. Moreover, they are more destructive in the stator teeth with higher local flux density and difficulties of cooling. Therefore, core quality assessment, to identify any inter-laminar fault in the magnetic cores, should be performed at an early stage before it progresses to machine failure [9]. This is an essential criterion for efficient and reliable operation of the electrical machines and transforms. Examples of inter-laminar faults in a three-phase three-limb transformer core and a stator core are shown in Figs 1 and 2, respectively.

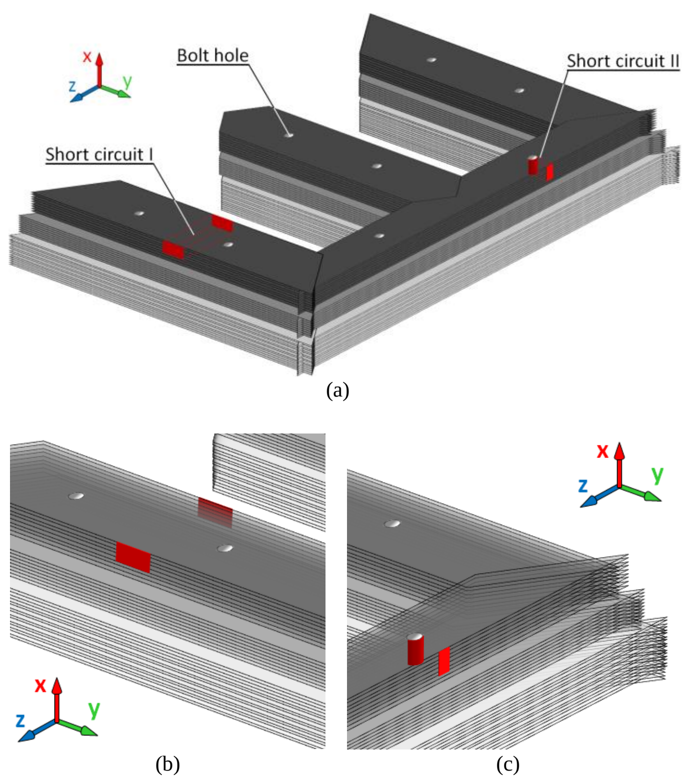

Fig 1 Perspective view of a three-phase three-limp transformer core with inter-laminar fault (a) Overall view (b) Inter-laminar fault on two sides of the limb and (c) Inter-laminar fault between bolt hole and yoke

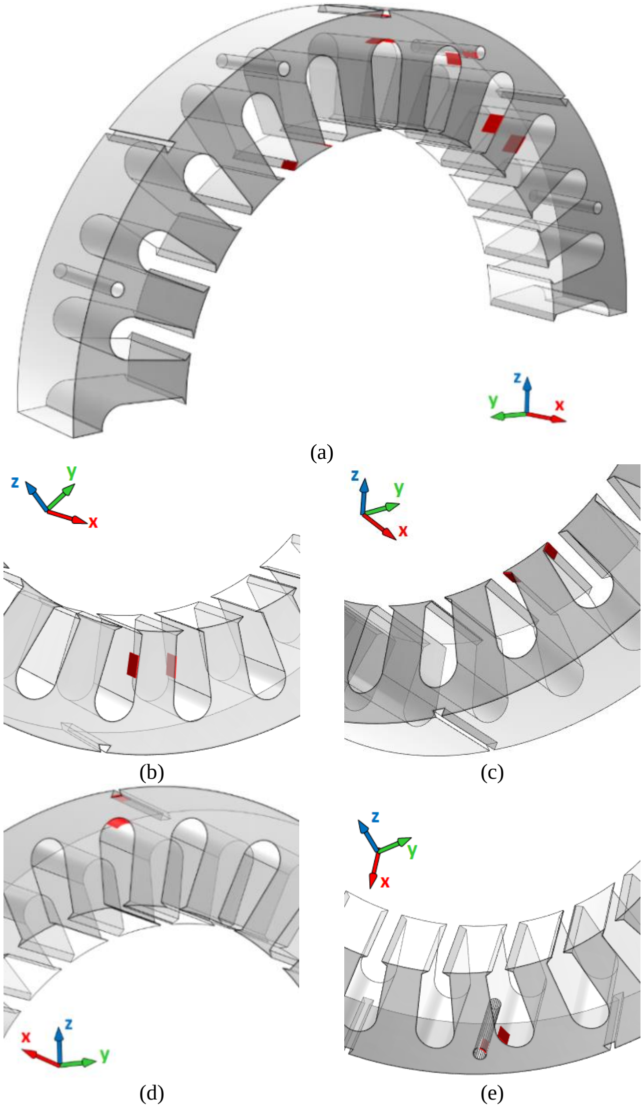

Fig 2 Perspective view of a stator core with inter-laminar fault (a) Overall view; with inter-laminar fault on (b) stator tooth (c) stator tooth tip (d) key-bar and slot, and (e) bolt hole and slot

Inter-laminar short circuit faults could occur during manufacturing/inspection processes, as well as during lifetime of the electrical machines and transformers [1]. Manufacturing processes include cutting the laminations to the required dimensions, punching and stamping, pressing or welding the outer circumference of the core to join the laminations. These manufacturing processes could deteriorate magnetic properties of the individual laminations and the assembled cores. Inter-laminar faults could also occur during the lifetime of the machines due to a number of reasons; e.g., stator-rotor rubs during assembly and operation, vibration of loose windings and laminations, arcing from winding failure, etc. [9-12].

It has been shown that cutting and punching of the laminations might cause microscopic edge burrs at the cut edges or around the punched holes and could lead to inter-laminar short circuits between the laminations [10-20]. Edge burrs are formed in various machining process as a result of plastic deformation during mechanical manufacturing processes, which has been identified as a major reason of inter-laminar fault in the magnetic cores [4]. In the design of the magnetic cores of the electrical machines and transformers, it is desirable to avoid punched holes on the laminations. For example, in the recent design of the transformers, clamping stress is applied using bands around the limb and yoke of the cores, instead of using bolt holes. However, punched holes are sometimes useful for cooling fluids, especially for stator cores of large machines, and hence it is important to study their impacts on the local and overall performance of the magnetic cores.

Inter-laminar fault problems and their impacts on the performance of the magnetic cores have been initially raised by the electrical machine and transformer manufacturers, and consequently became a major consideration for electrical steel manufacturers. Therefore, it is crucial for both parties to safeguard the magnetic cores against these kinds of defects to increase efficiency and reliability of the magnetic cores, and operating devices over the nominal range of frequency and flux density. During the last decades, various techniques have been developed and successfully implemented in core quality assessment and inter-laminar fault detection for magnetic cores of rotating machines [6-13] and transformers [16-19]. In almost all of these techniques, the magnetic cores under test are magnetised either totally [7-12] or locally [13] and a signal is measured resulting from the injected flux to detect possible inter-laminar faults. The difference between different methods is related to the measured signal and the sensor which is implemented to measure and interpret the fault signal.

In the past, detection of the hot spots in the stator cores of rotating machines was done qualitatively by turning off the power and immediately crawling into the bore and feeling the surface [13]. Core quality assessments were later done using an infrared camera set inside the machine, known as *full flux ring test method* or *loop test method* [13]. In this method, an external winding is wound around the yoke of the core to excite the magnetic core at 80~100 % of rated flux. After the magnetic core heats up, a thermal camera is used to detect hot spots in the core due to possible inter-laminar fault currents. The requirement for a power-full power supply to provide the nominal flux in the core, difficulty of detecting deep-seated faults, expensive thermal sensing equipment, and safety issues are the major drawbacks of this method [12].

In 1978 **El**ectromagnetic **C**ore **I**mperfection **D**etector (EL CID) as a low-flux test was invented to detect inter-laminar fault [11]. EL CID test method uses the same excitation configuration as the loop test but allows testing at 3~4 % of rated flux level, which significantly reduces the power requirement and safety risks [12]. In this test a flux sensing probe, including an air core coil of many turns bent into a "horse shoe" shape known as Chattock Coil or Maxwell Worm, is scanned in the axial direction along the surface of the core to detect irregular flux patterns caused by inter-laminar fault current [9]. In 2004 another electro-magnetic method was proposed in which the magnetic core is magnetised locally by means of a **F**lux **I**njection **P**robe (FIP). The measured power loss of the magnetised zone, also known as test zone, being indicative of the condition and quality of the test zone [12]. Almost all of the existing techniques were initially developed for stator cores of generators, but they could be modified and re-designed for transformer cores or other magnetic cores. A detailed review of these methods is performed in [14].

Hysteresis behaviour of the magnetic materials is an important feature in characterisation of the material under different magnetisation conditions. Performance of all types of the magnetic materials, e.g. soft magnetic materials, permanent magnet, etc. and their applications can be analysed and interpreted by means of a particular aspect of the hysteresis phenomenon. The area enclosed by the hysteresis loop represents the amount of energy dissipated into heat during one cycle. This is an important aspect of the hysteresis phenomenon to characterise the magnetic material and has found many applications in physics and engineering [20]. Accurate measurements of Static Hysteresis Loop (SHL) and Dynamic Hysteresis Loop (DHL), is an adequate technique of loss evaluation, over a wide range of magnetisation [20-25]. In this paper, a new approach based on the measured DHL is developed for core quality assessment purposes. The developed method can be implemented to detect inter-laminar fault between laminations of magnetic cores of transformers, electrical machines and other magnetic devices with laminated cores.

2. Test setup and sample preparation

Epstein size laminations (30 mm × 305 mm) of 0.3 mm thick CGO 3 % *SiFe*, with standard grades of M105-30P were provided by Cogent Power Ltd. Stacks of four laminations were prepared and labelled individually, to model different types of inter-laminar fault. Similar to the previous work [4], partial artificial short circuits of 10 mm wide with different configuration were introduced between the laminations. Lead-free solder was used to simulate the inter-laminar faults. Based on a survey performed in [4], lead-free solder was found to be an effective material to reproduce the effects of inter-laminar fault in clamped magnetic cores. Perspective view of the samples are shown in Fig 3, and described as follow:

Pack # 1: *Inter-laminar faults at three step-like points*
Pack # 2: *Inter-laminar faults at one set point*
Pack # 3: *Inter-laminar faults at three set points*

Prior to the experiments, sides of the stacks were inspected carefully, to prevent any additional inter-laminar fault due to, for example, foreign particles introduced during assembling and soldering. Each pack of lamination was magnetised separately using a single strip tester (SST) at peak flux densities of 1.1 T, 1.3 T, 1.5 T, and 1.7 T and magnetising frequencies from 50 Hz up to 1000 Hz. Two SSTs were used: A low frequency SST with primary and secondary winding turns of $N_1 = 865$ and $N_2 = 250$ for magnetising frequencies lower than 400 Hz, and a high frequency SST with reduced number of turns $N_1 = 108$ and $N_2 = 82$ for higher frequencies. Both SST conform to the British standard BS EN 10280:2007 [26]. More detail of the experimental setup is available in [27]. Magnetic properties of the samples including bulk power loss and DHL were measured and recorded individually.

A six channel thermometric measuring system using Type k thermocouple was already developed to measure localise temperature and localise power loss of electrical steels and magnetic cores, over a wide range of magnetisation [17]. The developed system was validated to monitor localise temperature with rates of rise from 0.2 milli-deg sec^{-1} to 40 milli-deg sec^{-1}, with a repeatability of better than 0.00431 and an uncertainty of better than ± 1.96 %. This system was successfully implemented to measure localise power loss of electrical steel laminations [17], and transformer cores [18] over the range of magnetisation. The developed system was used to measure localise temperature of the samples for the range of magnetisation.

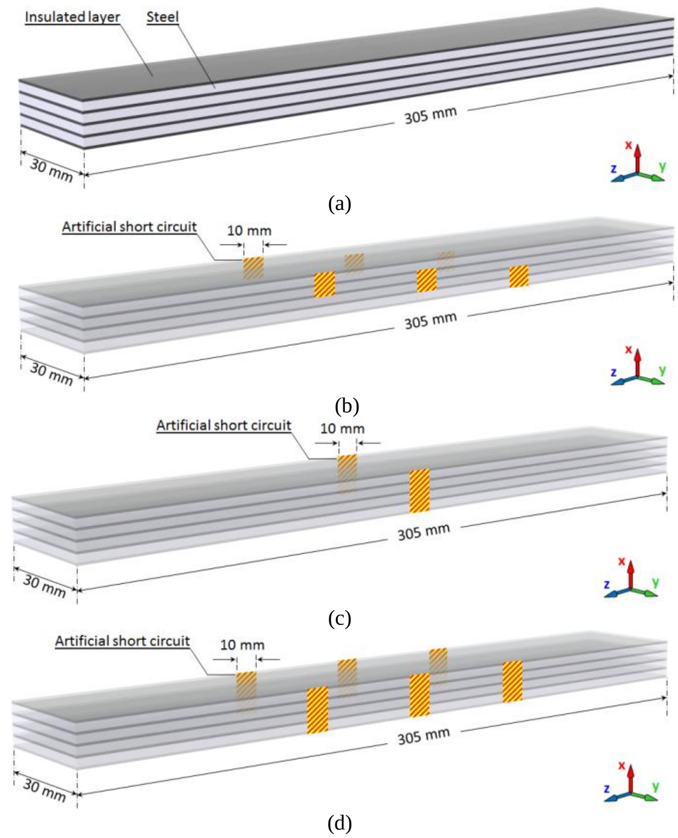

Fig 3 Perspective view of stacks of four laminations (a) without inter-laminar fault; and with inter-laminar faults (b) at three step-like points (pack # 1) (c) one set point (pack # 2) and (d) at three set points (pack # 3)

3. Experimental results

Impact of each artificial fault on total power loss and local temperature of the specimen was evaluated using the SST and thermometric systems, described in section 2. The results are presented and discussed in the following subsections.

3.1. Power loss analysis based on the measured DHL:

DHL and bulk power loss of the specimen were measured and analysed for core quality assessment purposes. Bulk power loss of each stack was measured three times at each flux density and frequency in all experiments, with repeatability of better than 0.3 %. Experimental results presented in this paper are the average of three measurements. DHL and nominal power loss of a single lamination were initially measured; the results were considered as reference values to evaluate each pack of laminations. DHL of the specimens at a peak flux density of 1.7 T and measured frequencies are shown in Fig 4.

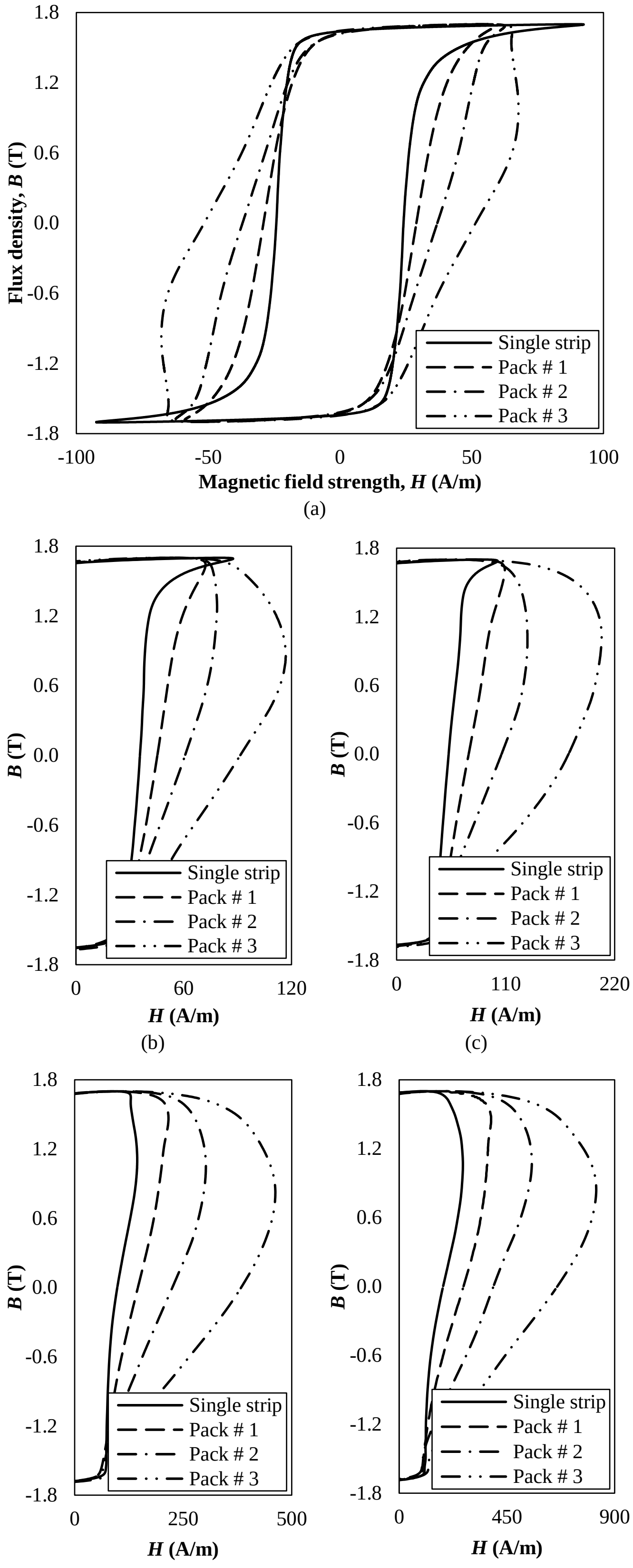

Fig 4 Dynamic hysteresis loops of the samples measured by SST under sinusoidal magnetisation at a peak flux density of B_{pk}=1.7 T and magnetising frequencies of (a) 50 Hz (b) 100 Hz (c) 200 Hz (d) 500 Hz and (e) 1000 Hz

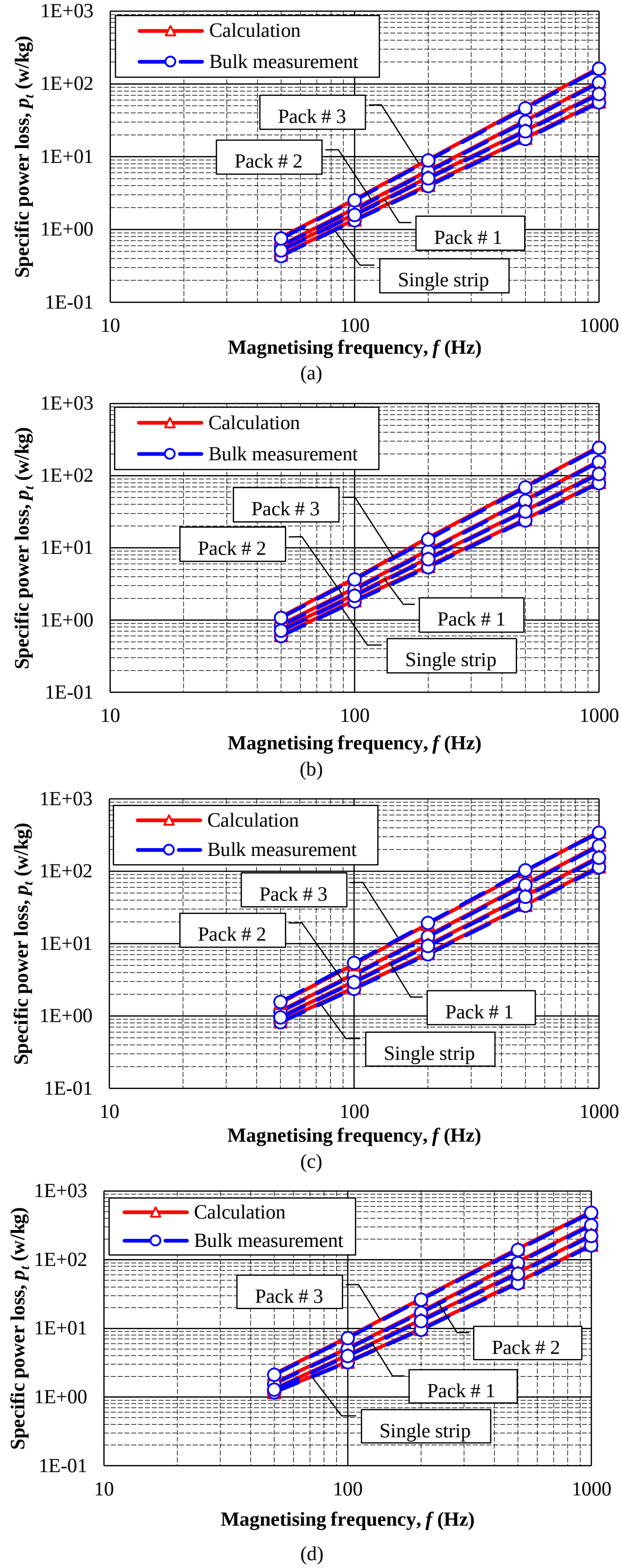

Fig 5 Comparison of specific power loss of the samples obtained from the DHL and bulk measurement at peak flux density of
(a) B_{pk}=1.1 T (b) B_{pk}=1.3 T (c) B_{pk}=1.5 T and (d) B_{pk}=1.7 T

The most evident feature of Fig 4 is the significant increase of the hysteresis loop area and the change in the loop shape, for different types of inter-laminar faults. This result reflects a unique property of the DHL in power loss evaluation, which can be implemented in the characterisation of the magnetic cores subjected to different kinds of inter-laminar fault scenarios. This concept is a powerful technique in core quality assessment of the electrical machines and can provide a meaningful comparison between magnetic properties of the magnetic cores subjected to different kinds of inter-laminar faults. An approach was developed to calculate the power loss of each stack from the measured DHL, for each flux density and frequency. The results were then compared with the bulk power loss of the samples. Fig 5 shows a comparison between the power loss of the samples calculated from the measured DHL and bulk measurement for the range of magnetisation. The results show a close agreement between the calculated power loss and bulk measurements, with a maximum difference of less than 4 %. Therefore, it can be concluded that inter-laminar faults in the magnetic cores, can be effectively detected by observing the dynamic hysteresis loop of the core. The results show high accuracy in fault detection and core quality assessment, even for low frequencies and low flux densities.

Fig 5 shows extra power loss in the shorted stacks compared to the nominal power loss of the material, which is caused by the fault current loops created by the inter-laminar faults. However, the results clearly indicate that each short circuit fault has a different impact on the total power loss. Effect of the artificial fault of pack # 2, with one fault current loop between the all laminations, is higher than that of pack # 1, with three individual fault current loops between the adjacent laminations. Furthermore, extra power loss caused by the inter-laminar fault of pack # 3 is almost three times higher than that of pack # 2. Based on an experimental survey performed in [4], it was shown that the artificial shorts of pack # 3 create three independent fault current loops in the stack, which results in an extra power loss three times higher than that of pack # 2, with a single fault. To make a better indication on the inter-laminar faults and their impacts on the power loss, the percent increases in bulk power loss of each pack, compared to the nominal power loss of the material over the magnetisation range are shown in Figs 6-a to 6-c, respectively. Fig 6 shows additional information regarding the impact of each artificial fault on the extra power loss of the stacks for each particular frequency and flux density. The results show that, the lowest increase in power loss is about 8 % for pack # 1 at magnetising frequency of 50 Hz and flux density of 1.1 T. Under the same magnetising condition, the percentage increase in the power loss of pack # 3 is about 60 %. The highest loss increase is 240 % for pack # 3 at magnetising frequency of 1000 Hz and peak flux density of 1.7 T.

3.2. Localise temperature measurement:

In the next part of this study, localise temperature of pack # 2 and pack # 3, with higher power loss, was measured using the thermometric system explained in section 2. To prevent the influence of ambient temperature on the measurement, the specimen were enclosed in an adiabatic chamber during the experiments.

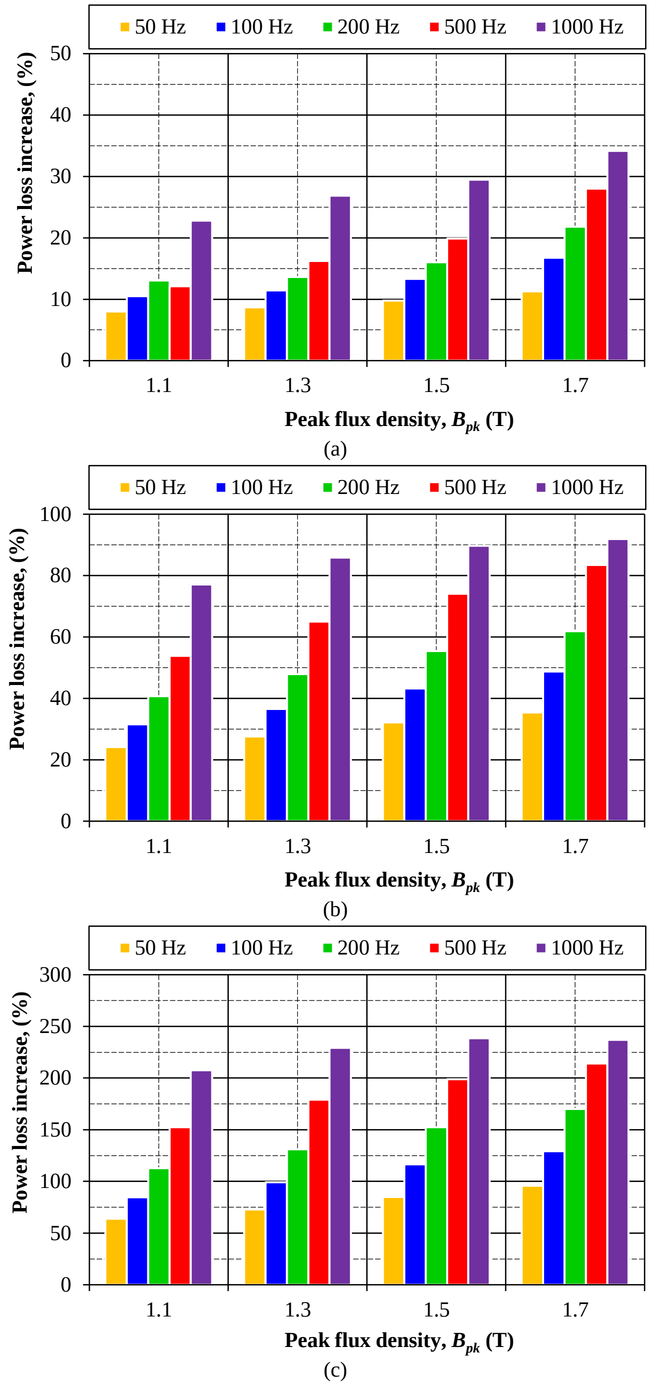

Fig 6 Percentage increase in bulk power loss of (a) pack # 1 (b) pack # 2 and (c) pack # 3, compare to the nominal loss of the material

A schematic top view of pack # 2 and pack # 3 and location of the thermocouples are shown in Figs 7-a and 8-a, respectively. To increase thermal contact between the thermocouples and surface of the laminations, double side thermal adhesive tape was used to stick the thermocouples on the laminations surface. Prior to the start of measurements, the samples were held under adiabatic condition for an appropriate time, to achieve a constant temperature in the samples and surroundings. This time is dependent on the material, magnetising frequency, and flux density.

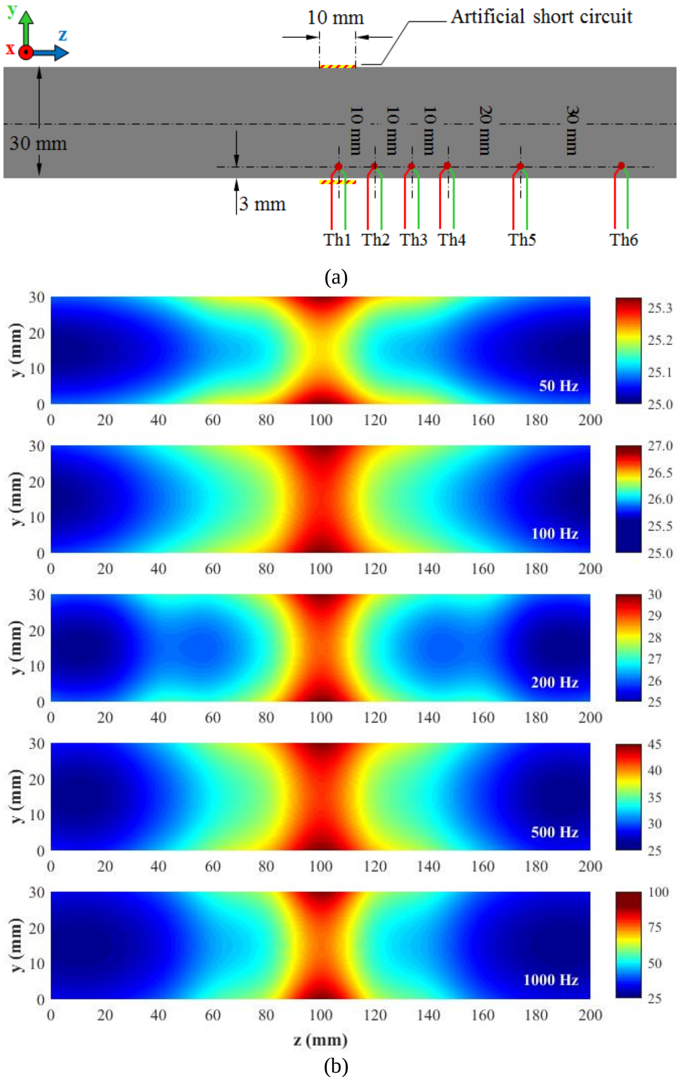

Fig 7 Surface temperature distribution of pack # 2 at peak flux density of B_{pk}=1.7 T (a) Thermocouple arrangement (b) Temperature distribution

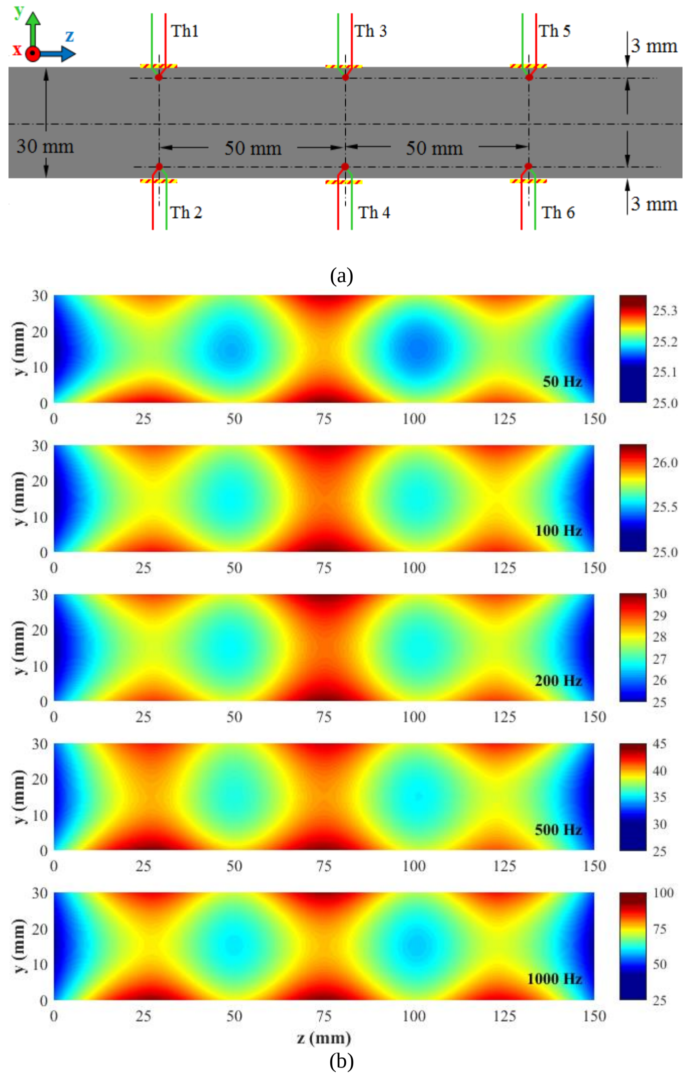

Fig 8 Surface temperature distribution of pack # 3 at peak flux density of B_{pk}=1.7 T (a) Thermocouple arrangement (b) Temperature distribution

The temperature was then monitored for 30 sec before magnetising the system, to ensure it is stable to within ± 0.02 °C of the initial ambient setting. The excitation voltage was then applied and the local temperature was measured over 60 sec, and recorded in separate databases. A final 60 sec interval was allocated at the end of each measurement to show the cooling curve of the specimen. A MATLAB code was developed to plot the surface temperature distribution of the samples; the results at a peak flux density of 1.7 T and the measured frequencies are shown in Figs 7-b and 8-b, respectively.

As expected initially and can be seen from Figs 7-b and 8-b, the highest temperature rise occurred at the centre of the fault current loops, close to fault point, with highest eddy current density. Furthermore, for each corresponding frequency, temperature distribution around the fault current loops in both packs are almost the same. This can proves the previous conclusion that the artificial short circuits applied on pack # 3 create three independent fault current loops in the stack, and hence there is no current flow between the fault current loops and shorted volumes.

Temperature rise (T-T_0) of pack # 2 measured by thermocouple Th # 1, and average temperature rise of pack # 3 measured by all thermocouples versus peak flux density for different magnetising frequencies are shown in Figs 9-a and 9-b, respectively. Fig 9 shows that the temperature rise due to the artificial short circuits at low frequencies and low flux densities is negligible. However, a significant increase in local temperature was observed for high magnetising frequencies and high flux densities. The maximum temperature rise at the shorted points during magnetising at a peak flux density of 1.7 T and a magnetising frequency of 1000 Hz was about 65 °C.

In IEEE standard 62.2-2004 [28] it is recommended that inter-laminar fault with a hot spot of 10 °C higher than the ambient (after 2 hours magnetisation), or 5 % increase in the magnetic loss should be considered as serious defects, and the magnetic core or the defected laminations should be replaced immediately. Therefore, even a small number of inter-laminar fault in the magnetic cores has a potential of machine failure and a serious treat for normal operation of the machine. Even though a few shorts between the laminations may not create a high localised temperature, it could result in a significant amount of energy loss during the lifetime of the machine. Furthermore, thermal stress caused by the inter-laminar faults accelerates the degradation of the insulating material of the magnetic cores and the premature aging of the magnetic core and the machine [15].

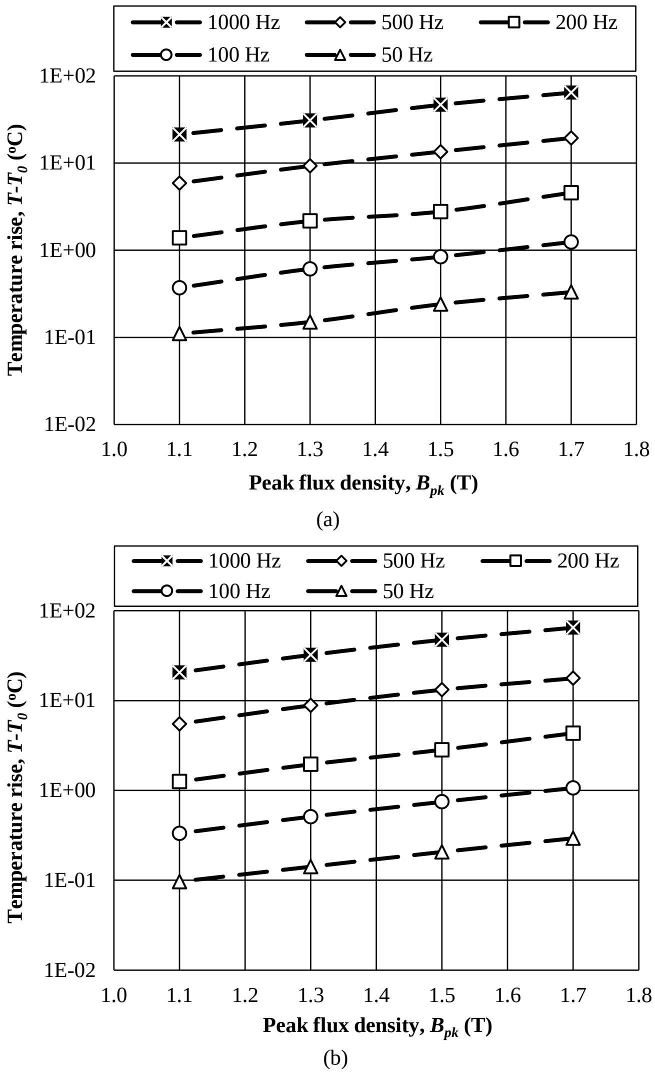

Fig 9 Temperature rise at fault location measured by (a) Th # 1 on pack # 2 and (b) average temperature measured by all thermocouples on pack # 3

4. Conclusion

In this paper, a new approach was developed to evaluate the quality of the magnetic cores of the electrical machines and transformers, based on the measured dynamic hysteresis loop. The accuracy of the method was validated on stacks of four laminations subjected to different kinds of inter-laminar faults, over a wide range of frequency and flux density. The results show a close agreement between the calculated power loss obtained from the developed approach and bulk measurements, with a maximum difference of less than 4 %. Therefore, the developed approach can be effectively implemented to characterise magnetic properties and condition monitoring of the magnetic cores of electrical machines and transformers, over a wide range of flux density and frequency. A thermometric method was also implemented to visualise surface temperature distribution of the samples. This technique is capable of measuring localise power loss and localise temperature to detect the hot spot in the magnetic cores.

5. Acknowledgment

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6. References

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